

XUV Lasers by Quartet to Doublet Energy Transfer in Alkali Atoms

JOSHUA E. ROTHENBERG AND STEPHEN E. HARRIS, FELLOW, IEEE

Abstract—The paper describes and compares several systems in neutral Li and K for constructing lasers in the XUV spectral region. The systems are based on population storage in metastable quartet levels, with subsequent laser transfer to doublet levels which are themselves stable against autoionization.

RAPIDLY decreasing spontaneous emission times at shorter wavelengths make it likely that lasers in the spectral region below 1000 Å will operate by first storing population in a metastable level [1], [2]. An intense, short pulse tunable laser would then be used to rapidly transfer this population to the upper level of the lasing transition.

In a recent paper [3], it was proposed that the quartet levels of alkali atoms be used for storage, with subsequent transfer to a level in the doublet series. The doublet level will typically be chosen so that, to first order, it is coulombically stable against autoionization. Lasing would occur to a lower level in the doublet series. Energy level diagrams for the proposed technique as it applies to systems in lithium and potassium are shown in Fig. 1.

In both cases, the storage levels are pure quartets and lie at or near the bottom of the quartet manifold. The levels are populated by direct electron excitation (optical fluorescence within the quartet manifold of Li has been observed for many years [4]), and it is expected that they may also be populated by recombination and by charge transfer. Natural lifetimes of the Li $1s2s2p^4P_{5/2}^0$ and K $3p^54s4p^4D_{7/2}$ levels of 5.8 and 90 μ s, respectively, have been measured by Feldman and Novick [5].

Radiative emission at 207 Å, originating from the even parity (upper laser) level in neutral Li has been seen in a beam foil experiment [6], and more recently in a microwave excited plasma [7].

A key reason for studying the quartet to doublet transfer systems of this paper, as opposed to triplet to singlet systems in the ion [1], [2] (for example, $\text{Li}^+1s2s^3S \rightarrow \text{Li}^+1s2p^1P \rightarrow \text{Li}^+1s^2$), is that the systems of this paper provide a lower laser level which is not the ground level of the species. This level may be emptied by the same laser used for the quartet to doublet transfer, or perhaps by a second laser tuned to a discrete level near to the lowest continuum.

The technique described here is based on at least a partial breakdown of LS coupling, thereby allowing transfer on the

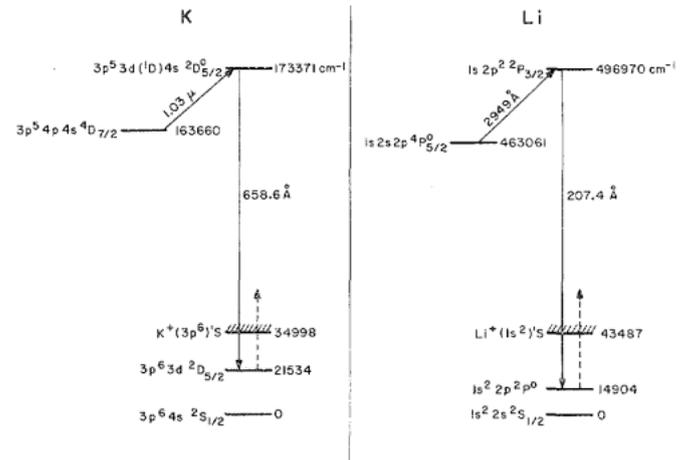


Fig. 1. Energy level diagrams for quartet to doublet transfer in Li and K. An incident laser is used to transfer population from a quartet storage level to a doublet (upper) laser level. The same laser, or a second laser, is used to deplete the lower laser level.

intercombination line connecting the quartet to the doublet series. For low levels of light atoms such as Li, the breakdown of LS coupling is small and laser power densities of about 10^{11} W/cm² are required for complete transfer in a time short compared to the spontaneous emission time. There are two ways to increase the breakdown of LS coupling and to thereby reduce the necessary laser power density for transfer. The first is to work in a heavier atom, such as K, which has a larger coulombic gradient and therefore a larger spin-orbit matrix element. The second is to use a storage level which is somewhat higher in the quartet manifold and to thereby make use of smaller energy denominators between appropriate levels in the quartet and doublet series.

Either of these approaches has several additional effects. Of most importance, the breakdown of LS coupling allows an admixing of terms within the doublet series. This, in turn, may allow autoionization of the upper laser level, thereby reducing the gain cross section, and requiring that the population transfer take place in a shorter time. Also, to the extent that long storage times are desired, one may only use those quartet levels which have the maximum value of J for a particular configuration. Irrespective of the breakdown of LS coupling, these levels are pure quartets and should not autoionize coulombically.

In the following sections of the paper we will give the results of calculations and estimates for several quartet-doublet transfer systems in K and Li, and will compare the results with those obtained earlier in Li. Additional systems in Na and Rb will be briefly discussed.

Manuscript received August 5, 1980; revised October 3, 1980. This work was supported by the U.S. Office of Naval Research. The work performed by J. E. Rothenberg was supported by the Fannie and John Hertz Foundation.

The authors are with the Edward L. Ginzton Laboratory, Stanford University, Stanford, CA 94305.

TABLE I
LS COUPLED BASIS STATES AND ABBREVIATIONS FOR THE $3p^5 3d 4s$
 $J = 5/2$ CONFIGURATION

$ \Phi_i\rangle$	Abbreviation
$3p^5 3d(^1D)4s \ ^2D_{5/2}^o$	$(^1D)^2D$
$3p^5 3d(^3D)4s \ ^2D_{5/2}^o$	$(^3D)^2D$
$3p^5 3d(^1F)4s \ ^2F_{5/2}^o$	$(^1F)^2F$
$3p^5 3d(^3F)4s \ ^2F_{5/2}^o$	$(^3F)^2F$
$3p^5 3d(^3D)4s \ ^4D_{5/2}^o$	$(^3D)^4D$
$3p^5 3d(^3F)4s \ ^4F_{5/2}^o$	$(^3F)^4F$
$3p^5 3d(^3P)4s \ ^4F_{5/2}^o$	$(^3P)^4P$

TABLE II
ESTIMATED ELECTROSTATIC AND SPIN-ORBIT PARAMETERS FOR THE
 $3p^5 3d 4s$ CONFIGURATIONS OF POTASSIUM

$F^2(pd) = 32116 \text{ cm}^{-1}$
$G^1(pd) = 37129$
$G^3(pd) = 21598$
$G^1(ps) = 2687$
$G^2(sd) = 12577$
$\varphi_p = 1391$
$\varphi_d = 14$

POTASSIUM

A. Diagonalization of the Hamiltonian; Eigenfunctions

Much of the work in this section is based on the spectroscopic results and calculations of Mansfield and Ottley [8] and Mansfield [9]. The key step in the calculation is to find the $J = 5/2$ eigenfunctions of the $3p^5 3d 4s$ configuration as components of an LS coupled basis set. Matrix elements of the (true) eigenfunctions are then obtained as sums of the products of mixing coefficients and matrix elements within the basis set. The basis states, along with the abbreviations we will use, are listed in Table I.

The eigenfunctions are found by diagonalizing the Hamiltonian matrix in this basis. Following Mansfield [9], the electrostatic matrix elements are found from Slater [10]. We used the formulas given for the $p^5 d$ configuration and used Van Vleck's theorem for the addition of the s electron. The Slater-Condon parameters were calculated by Mansfield in a single configuration Hartree-Fock calculation [9], and were subsequently modified by Mansfield and Ottley [8]. These parameters are shown in Table II. The spin-orbit matrix elements can be calculated directly from Roth [11] in terms of the radial parameters φ_p and φ_d . φ_p and φ_d were calculated in [9] and modified in [8], and they are also given in Table II. The parameter φ_d is much smaller than φ_p and we have neglected its contribution.

The results of the diagonalization of this matrix are given in

TABLE III
STATE COMPOSITIONS AND THEIR POSITIONS FOR THE CONFIGURATION
 $3p^5 3d 4s$ WITH $J = 5/2$

Eigenstate	State Mixing Coefficients							Relative Position (cm ⁻¹)
	$c(^1D)^2D$	$c(^3D)^2D$	$c(^3D)^4D$	$c(^1F)^2F$	$c(^3F)^2F$	$c(^3F)^4F$	$c(^3F)^4P$	
$ \psi(^1D)^2D\rangle$	0.92	0.32	0.21	-0.007	0.068	0.04	-0.06	0
$ \psi(^3D)^2D\rangle$	-0.32	0.92	0.005	0.17	-0.13	0.01	-0.005	4153
$ \psi(^1F)^2F\rangle$	0.12	-0.17	-0.11	0.91	-0.34	0.05	0.005	646
$ \psi(^3D)^4D\rangle$	-0.17	0.10	0.96	0.07	-0.13	-0.08	-0.04	-1365
$ \psi(^3F)^2F\rangle$	-0.10	0.02	0.10	0.37	0.92	0.10	0.001	-1764
$ \psi(^3F)^4F\rangle$	-0.05	-0.03	0.07	-0.08	-0.09	0.99	-0.001	-5685
$ \psi(^3F)^4P\rangle$	0.05	0.02	0.06	-9×10^{-5}	1×10^{-11}	6×10^{-11}	0.997	-13919

$$\text{where } |\psi\rangle = \sum_i c(i) |\Phi_i\rangle$$

Table III, where the eigenstates are named by their principal components and the eigenenergies are relative to that of the $(^1D)^2D$ eigenstate.

B. Intercombination Line Oscillator Strength

Expanding in the LS basis, $\{|\Phi_i\rangle\}$, the line strength of a transition, is given by

$$\begin{aligned}
 S_{if} &= |\langle \psi_i | \vec{R} | \psi_f \rangle|^2 \\
 &= \left| \sum_{jk} \langle \psi_i | \Phi_j \rangle \langle \Phi_j | \vec{R} | \Phi_k \rangle \langle \Phi_k | \psi_f \rangle \right|^2 \\
 &\equiv \left| \sum_{jk} C_{ij} \cdot M_{jk} \cdot C_{kf} \right|^2.
 \end{aligned} \tag{1}$$

The storage level $3p^5 4s 4p^4 D_{7/2}$ has the maximum angular momentum for this configuration and is a pure LS level. The incident (transfer) laser at $\lambda = 1.03 \mu$ (see Fig. 1) couples this storage level to the $J = 5/2$ levels of the $3p^5 3d 4s$ configuration, with weighting factors C_{ij} determined from Section A. For the intercombination transition $3p^5 4p 4s^4 D_{7/2} \rightarrow 3p^5 3d(^1D)4s^2 D_{5/2}^o$, we must calculate the M_{jk} for $3p^5 4p 4s^4 D_{7/2} \rightarrow 3p^5 3d 4s^4 L_{5/2}^o$ where $L = P, D$, or F . Following the procedure of Shore and Menzel [12],

$$M = R_{\text{line}} \cdot R_{\text{mult}} \cdot \mathcal{J} \tag{2}$$

where R_{line} and R_{mult} are tabulated and \mathcal{J} is the one electron matrix element $\mathcal{J} = \langle 4p || r || 3d \rangle$. \mathcal{J} was found from tabulated line strengths [13] of argon ($3p^5 4p \rightarrow 3p^5 3d$) and potassium ($3p^6 3d \rightarrow 3p^6 4p$). The calculated values of the M_{jk} (in atomic units) are given in Table IV. Summing over the components as per (1), we obtain $S = 1.95 \times 10^{-3} \mathcal{J}^2 = 0.16$, which corresponds to an oscillator strength for the intercombination transition $3p^5 4p 4s^4 D_{7/2} \rightarrow 3p^5 3d(^1D)4s^2 D_{5/2}^o$ of $f = 6.0 \times 10^{-4}$.

C. Laser Transition

1) *Oscillator Strength:* The oscillator strength of the laser transition $3p^5 3d(^1D)4s^2 D_{5/2}^o \rightarrow 3p^6 3d^2 D_{5/2}$ is found in much the same way. The required M_{jk} are given in Table V. For this configuration, the multiplet factors are not given in Shore and Menzel and were calculated separately. \mathcal{J} was obtained from tabulated line strengths [13] of Ar or Cl. Again, from (1) and Table V, we obtain $S = 1.95 \mathcal{J}^2 = 0.63$, which

TABLE IV
LINE STRENGTH COMPONENTS FOR THE QUARTET TRANSFER
 $3p^5 4p 4s^4 D_{7/2} \rightarrow 3p^5 3d 4s^4 L_{5/2}^0$

Component	R_{LINE}	R_{MULT}	$J(4p, 3d)$	M_{jk}
${}^1D_{7/2} \rightarrow {}^1P_{5/2}$	1.26	0.129	9.1	1.48
${}^1D_{7/2} \rightarrow {}^1D_{5/2}$	-0.478	-0.5	9.1	2.17
${}^1D_{7/2} \rightarrow {}^1F_{5/2}$	0.090	1.18	9.1	0.97

TABLE V
LINE STRENGTH COMPONENTS FOR THE LASER TRANSITION
 $3p^5 3d(SL) 4s^2 L_{5/2}^0 \rightarrow 3p^6 3d^2 D_{5/2}$

Component	R_{LINE}	R_{MULT}	$J(4s, 3p)$	M_{jk}
$({}^1D) {}^2D_{5/2} \rightarrow {}^2D_{5/2}$	1.06	-0.913	0.570	-0.567
$({}^3D) {}^2D_{5/2} \rightarrow {}^2D_{5/2}$	1.06	-1.58	0.570	-0.955
$({}^1F) {}^2F_{5/2} \rightarrow {}^2D_{5/2}$	0.239	1.08	0.570	0.147
$({}^3F) {}^2F_{5/2} \rightarrow {}^2D_{5/2}$	0.239	1.87	0.570	0.255

corresponds to an oscillator strength of the laser transition $3p^5 3d({}^1D) 4s^2 D_{5/2}^0 \rightarrow 3p^6 3d^2 D_{5/2}$ of $f = 0.049$.

2) *Linewidth*: The autoionizing width of the upper laser level $3p^5 3d({}^1D) 4s^2 D_{5/2}^0$ is not known and must be estimated. In pure LS coupling, coulombic autoionization is not allowed. This is because, due to parity, the only continua available to the $3p^5 3d 4s$ configuration are 2P and 2F . However, as per Table III, the spin-orbit interaction mixes the 2D state with 2F states which do autoionize. If the 2F states have an autoionizing rate of A_F , then the upper laser level would autoionize at a rate of about $(5 \times 10^{-3})A_F$. Since we do not know A_F , we will take it equal to the measured linewidth [14], [15] of the broad doublet states $3p^5 4s^2 {}^2P_{1/2, 3/2}^0$. This $\sim 60 \text{ cm}^{-1}$ width implies $A_F \cong 1.2 \times 10^{13} \text{ s}^{-1}$, corresponding to an autoionizing time and width of the upper laser level of 17 ps and 0.31 cm^{-1} , respectively. This is somewhat less than the Doppler width, at 400°C , of 0.45 cm^{-1} .

D. Laser Gain

The calculated oscillator strength of $f = 0.049$, a Voigt profile with a Doppler component of 0.45 cm^{-1} , and a Lorentzian component of 0.31 cm^{-1} yield a cross section for stimulated emission on the $3p^5 3d({}^1D) 4s^2 D_{5/2}^0 \rightarrow 3p^6 3d^2 D_{5/2}$ transition at 658.6 \AA of $\sigma_{\text{gain}} = 5.3 \times 10^{-14} \text{ cm}^2$.

To calculate the steady-state gain we assume that the $3p^5 4p 4s^4 D_{7/2}$ storage level is undepleted by the transfer laser. The steady-state population of the upper laser level is then given by

$$N^* = \left[\frac{\sigma_{\text{IC}}(P/A)}{\hbar\omega} \right] \tau_{\text{AI}} N_{\text{storage}} \quad (3)$$

where σ_{IC} is the absorption cross section of the intercombination line, $\hbar\omega$ is the photon energy of the transfer laser, P/A is

the intensity of the transfer laser, τ_{AI} is the estimated autoionizing time of the $3p^5 3d({}^1D) 4s^2 D_{5/2}^0$ level, and N_{storage} is the population of the storage level. The line shape of the intercombination transition is again a Voigt profile, but with a Doppler component of 0.03 cm^{-1} . Based on the calculated oscillator strength we have $\sigma_{\text{IC}} = 1.0 \times 10^{-15} \text{ cm}^2$, and, with the previously estimated value of $\tau_{\text{AI}} = 17 \text{ ps}$, we obtain

$$N^* = (8.3 \times 10^{-8}) \frac{P}{A} \cdot N_{\text{storage}} \quad (4)$$

where P/A is in units of W/cm^2 . The steady-state laser gain is then

$$\text{gain} = N^* \sigma_{\text{gain}} = (4.5 \times 10^{-21}) \frac{P}{A} (\text{W/cm}^2) \cdot N_{\text{storage}} (\text{cm}^{-3}) \text{cm}^{-1}. \quad (5)$$

As a consequence of the nondepletion assumption made, this formula only applies for an applied laser power density, at 1.03 \mu m , which is less than the saturation power density $(P/A)_{\text{sat}} = \hbar\omega/2\sigma_{\text{IC}}\tau_{\text{AI}} = 6 \times 10^6 \text{ W/cm}^2$. The results of the calculation are summarized in Table VI, column 1.

LITHIUM

In a recent paper, Nussbaumer [16] has calculated oscillator strengths and branching ratios for the 207 \AA Li system proposed by Harris [3]. Based on these calculations, column II of Table VI gives revised numbers for this system. The cross sections of the transitions are based on Voigt line shapes with a natural component of 0.11 cm^{-1} . The Doppler components are based on an assumed temperature of 800°C . They are 4.3 and 0.3 cm^{-1} on the 207 and the 2949 \AA transitions, respectively.

Fig. 2 shows another system in Li, with a laser transition at 200.3 \AA . This system should have a larger intercombination line strength and should require less laser power density for transfer than does the 207 \AA system. The transfer wavelength of 4671 \AA is also somewhat more convenient. Here, energy is stored in the $1s 2s 4p^4 P_{5/2}^0$ quartet level [17]. Although this level is metastable against autoionization, it may radiate to the $1s 2s 3s^4 S_{3/2}$ level with an estimated lifetime of a few hundred nanoseconds. The upper laser level is that which Bunge [18] denotes as $[1s 2p({}^3P) 4p - 1s 2p({}^1P) 3p]^2 P_{3/2}$. For the lasing transition at 200.3 \AA , Bunge calculates an oscillator strength of 0.068 and a branching ratio of 0.93 . Fluorescence at this wavelength was recently reported by Willison *et al.* [7].

The reason for the choice of this system is the near coincidence (401 cm^{-1}) of the $1s 2p 4p^4 P_{3/2}$ level with the upper laser level. The dominant perturbation sequence for the calculation of the intercombination line strength is $1s 2s 4p^4 P_{5/2}^0 \rightarrow 1s 2p 4p^4 P_{3/2} \rightarrow [1s 2p({}^3P) 4p - 1s 2p({}^1P) 3p]^2 P_{3/2}$. As an approximation we assume that the radial portion of the spin-orbit matrix element for the second step of this sequence is the same as that calculated by Nussbaumer for the intermediate step $1s 2p^2 {}^4 P_{3/2} \rightarrow 1s 2p^2 {}^2 P_{3/2}$. The intercombination line oscillator strength of this system, as compared to the 207 \AA system, then scales as the square of the energy denominators

TABLE VI
SUMMARY OF RESULTS

	K	Li	Li
Storage Level	$3p^5 4s 4p \ ^4D_{7/2}$	$1s 2s 2p \ ^4P_{5/2}^o$	$1s 2s 4p \ ^4P_{5/2}^o$
Intercombination Transition	$3p^5 4s 4p \ ^4D_{7/2} \rightarrow 3p^5 3d(^1D) 4s \ ^2D_{5/2}^o$	$1s 2s 2p \ ^4P_{5/2}^o \rightarrow 1s 2p^2 \ ^2P_{3/2}$	$1s 2s 4p \ ^4P_{5/2}^o \rightarrow [1s 2p(^3P) 4p - 1s 2p(^1P) 3p] \ ^2P_{3/2}$
Laser Transition	$3p^5 3d(^1D) 4s \ ^2D_{5/2}^o \rightarrow 3p^6 3d \ ^2D_{5/2}$	$1s 2p^2 \ ^2P_{3/2} \rightarrow 1s^2 2p \ ^2P^o$	$[1s 2p(^3P) 4p - 1s 2p(^1P) 3p] \ ^2P_{3/2} \rightarrow 1s^2 3p \ ^2P^o$
Laser Wavelength	658.6 Å	207.4 Å	200.3 Å
Intercombination Wavelength	1.03 μ	2949 Å	4671 Å
f_{laser} (emission)	0.049	0.129	0.068
f_{IC} (absorption)	6.0×10^{-4}	2.5×10^{-8}	7.4×10^{-7}
σ_{gain} (cm ²)	5.3×10^{-14}	2.4×10^{-14}	1.3×10^{-14}
σ_{IC} (cm ²)	1.0×10^{-15}	5.1×10^{-20}	2.4×10^{-18}
τ_{rad}	1.3 ns	49 ps	83 ps
τ_{AI}	17 ps	$> \tau_{rad}$	$> \tau_{rad}$
(P/A) _{sat} (a)	6×10^6 W/cm ²	1.3×10^{11} W/cm ²	1.0×10^9 W/cm ²
Gain Coefficient κ (b)	4.5×10^{-21}	9.1×10^{-26}	6.0×10^{-24}

(a) $(P/A)_{sat} = \hbar\nu / (2\tau\sigma_{IC})$ is the laser power density which saturates the intercombination line. τ is the smaller of the autoionizing and radiative lifetimes.

(b) The gain coefficient κ is defined so that $Gain = \kappa N(\text{cm}^{-3}) (P/A) (\text{W}/\text{cm}^2) \text{cm}^{-1}$, where N is the population density of the storage level.

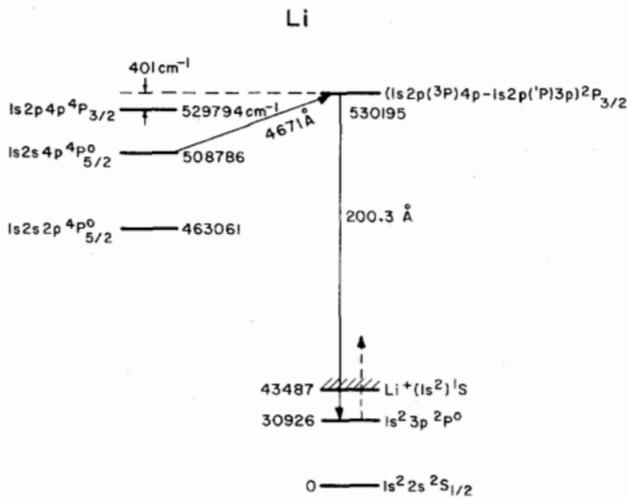


Fig. 2. Energy level diagram for a 200.3 Å system in Li.

$(6967/401)^2$ and as the square of the spin-orbit matrix element. The mixed final level and the fact that only one electron participates reduce the square of the spin-orbit matrix element by a factor of 7.9. Including the multiplet factor of 0.5 this yields an intercombination oscillator strength of $f = 7.4 \times 10^{-7}$. This estimate neglects spin-other-orbit and spin-spin contributions.

The remainder of the calculation proceeds as before. The natural and Doppler components of the 200.3 Å transition are 0.064 and 4.4 cm^{-1} , respectively. The intercombination tran-

TABLE VII
OTHER ALKALI SYSTEMS

Alkali Atom	Transition	Transfer Wavelength	Laser Wavelength
Na	$2p^5 3s 3p \ ^4D_{7/2} \rightarrow 3p^5 3s(^3P) 3d \ ^2D_{5/2}^o \rightarrow 3p^6 3d \ ^2D$	~ 3900 Å	~ 380 Å
Rb	$4p^5 5s 5p \ ^4D_{7/2} \rightarrow 4p^5 4d(^1D) 5s \ ^2D_{5/2}^o \rightarrow 4p^6 4d \ ^2D$	4721 Å	773.7 Å

sition at 4671 Å has a Doppler width of 0.19 cm^{-1} . The results are given in column III of Table VI.

OTHER ALKALI ATOMS

Table VII shows possible systems in Rb and Na. Level positions and identifications for Na and Rb were obtained from Weiss [19] and Mansfield [20], respectively. These systems are duals of the K system. In both cases the storage level is the lowest level in the quartet manifold. We have not calculated any of the other parameters.

SUMMARY

The increased breakdown of LS coupling as we proceed from Li to K has had two effects. 1) Due to the large mixing of the quartet and doublet series, the oscillator strength and absorption cross section of the intercombination line have been significantly increased, thereby reducing the necessary power density

of the transfer laser. 2) As a result of level mixing, the lifetime of the upper laser level in K is determined by autoionization, instead of by spontaneous emission. Although this autoionization time is not known, we believe that we have established a reasonable lower bound.

A second potential laser system has been identified in Li. Here, a greater breakdown in LS coupling is achieved by selecting storage and target levels which are coupled by a near resonant intermediate level.

The results of the calculations on the two new systems, as well as revised calculations on the original 207 Å system in Li, are summarized in Table VI.

Possible laser systems are suggested in Na and Rb, and are summarized in Table VII.

ACKNOWLEDGMENT

The authors acknowledge helpful discussions with T. Luca-torto and A. Weiss of the National Bureau of Standards.

REFERENCES

- [1] H. Mahr and U. Roeder, "Use of metastable ions for a soft x-ray laser," *Opt. Commun.*, vol. 10, pp. 227-228, 1974.
- [2] S. A. Mani, H. A. Hyman, and J. D. Daugherty, "Lithium-ion soft x-ray laser," *J. Appl. Phys.*, vol. 47, pp. 3099-3106, 1976.
- [3] S. E. Harris, "Proposal for a 207Å laser in lithium," *Opt. Lett.*, vol. 5, pp. 1-3, 1980.
- [4] G. Herzberg and H. R. Moore, "The spectrum of Li^+ ," *Can. J. Phys.*, vol. 37, pp. 1293-1313, 1959.
- [5] P. Feldman and R. Novick, "Autoionizing states in the alkali atoms with microsecond lifetimes," *Phys. Rev.*, vol. 160, pp. 143-158, 1967.
- [6] J. P. Buchet, M. C. Buchet-Poulizac, and H. G. Berry, "Classifications of some transitions in doubly excited Li I and Li II," *Phys. Rev. A*, vol. 7, pp. 922-924, 1973.
- [7] J. R. Willison, R. W. Falcone, J. C. Wang, J. F. Young, and S. E. Harris, "Emission spectra of core-excited even parity 2P states of neutral lithium," *Phys. Rev. Lett.*, vol. 44, pp. 1125-1128, 1980.
- [8] M.W.D. Mansfield and T. W. Ottley, "The identification of low energy K and Ca^+ autoionizing levels observed in electron impact experiments," in *Proc. Roy. Soc. London A*, vol. 365, pp. 413-424, 1979.
- [9] M.W.D. Mansfield, "The K I absorption spectrum in the vacuum ultraviolet: 3p-subshell excitation," in *Proc. Roy. Soc. London A*, vol. 346, pp. 539-553, 1975.
- [10] J. C. Slater, *Quantum Theory of Atomic Structure*, vol. II. New York: McGraw-Hill, 1960, pp. 286-293.
- [11] C. Roth, "Spin-orbit interactions of the configuration $l^{n-1}l'$," *J. Math. Phys.*, vol. 9, pp. 1832-1834, 1968.
- [12] B. W. Shore and D. H. Menzel, *Principles of Atomic Spectra*. New York: Wiley, 1968, ch. 10.
- [13] W. L. Wiese, M. W. Smith, and B. M. Miles, *Atomic Transition Probabilities*, U.S. Nat. Bureau Stand., Rep. NSRDS-NBS 22, vol. II, Washington, DC: U.S. Govt. Printing Office, 1969, pp. 194-195, 229, 192, and 159.
- [14] R. D. Driver, "A measurement of the 3p subshell photoionization cross section of potassium," *J. Phys. B*, vol. 9, pp. 817-827, 1976.
- [15] R. D. Hudson and V. L. Carter, "Experimental values of the atomic absorption cross section of potassium between 580 Å and 1000 Å," *J. Opt. Soc. Amer.*, vol. 57, pp. 1471-1474, 1967.
- [16] H. Nussbaumer, "Atomic data for a Li I 207 Å laser," *Opt. Lett.*, vol. 5, pp. 222-224, 1980.
- [17] C. F. Bunge and A. V. Bunge, "Absolute term values for the quartet states of neutral lithium," *Phys. Rev. A*, vol. 17, pp. 816-821, 1978.
- [18] C. F. Bunge, "Accurate calculations for the even-parity core-excited 2P states of neutral Li," *Phys. Rev. A*, vol. 19, pp. 936-942, 1979.
- [19] A. W. Weiss, private communication.
- [20] M.W.D. Mansfield, "A new interpretation of the Rb I 4p subshell excitation spectrum between 15 eV and 19 eV," *Proc. Roy. Soc. London A*, vol. 364, pp. 135-144, 1978.



Joshua E. Rothenberg was born in New York City, NY, on September 8, 1958. He received the B.S. degree in applied physics and the M.S. degree in electrical engineering from the California Institute of Technology, Pasadena.

In 1978 he was the recipient of a Hertz Foundation Fellowship to study at Stanford University, Stanford, CA, where he has been working in the area of XUV spectroscopy and lasers.

Mr. Rothenberg is a member of Tau Beta Pi.



Stephen E. Harris (S'59-M'64-F'72) was born in Brooklyn, NY, in November 1936. He received the B.S. degree from Rensselaer Polytechnic Institute, Troy, NY, in 1959 and the M.S. and Ph.D. degrees from Stanford University, Stanford, CA, in 1961 and 1963, respectively, all in electrical engineering.

Since 1963 he has been on the faculty of Stanford University where he is now a Professor of Electrical Engineering and Applied Physics. His research work has been in the fields of lasers, quantum electronics, nonlinear optics, and acousto-optics. His present research interests are in the areas of laser induced inelastic collisions and in the development of new techniques for generating vacuum ultraviolet and XUV radiation.

Prof. Harris was the recipient of the 1973 Curtis McGraw Research Award and the 1978 David Sarnoff Award. He is a Fellow of the Optical Society of America and the American Physical Society, and a member of the National Academy of Engineering.